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SOIL PHYSICOCHEMICAL PROPERTIES IN DIFFERENT STAND AGES AND SOIL DEPTHS OF *Acacia Mangium* PLANTATION

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Abstract: Soil physicochemical properties are essential to support tree stand growth and vital for the optimum wood biomass production in forest plantation management. This study aims to determine the soil physical and chemical properties in different stand ages and soil depths of an *A. mangium* plantation. Data were collected from the Daiken Sarawak Sdn Bhd forest plantation area. Soil profiles were established in five stand ages of 3.7, 5.8, 8.5, 10.8 and 12.7 years old, and an unplanted area is used as a reference. Soil samples were collected from depths of 0–20, 20–40, 40–60, 60–100 cm from each of the stand ages and the reference site. The soil organic matter (SOM) and total carbon increased with the increase in stand ages. The soil texture was sandy clay loam soil. The soil is extremely acidic. The SOM, total carbon, pH and total nitrogen decreased with soil depths. Soil in the reference site had the highest pH, SOM percentage, total carbon and total nitrogen. Among the stand ages, the oldest stand age had the highest amount of total soil nitrogen. The cation exchange capacity was the highest in the intermediate stand ages. The soil properties in 10.8- and 12.7-year-old stand were closely comparable to that of the reference site.

Keywords: *Acacia mangium,* forest plantation, soil physicochemical properties, stand ages, soil depths.

Introduction

Acacia mangium is one of the essential pioneers of the timber plantation industry in Malaysia's reforestation programme. It is known as one of the unique timber trees in tropical forests as it is fast-growing and can undergo nitrogen-fixing by itself (Lee *et al.,* 2015). Due to better site adaptability and growth performance, more than 85% of the Malaysian Compensatory Forest Plantation Project (CFPP) area had been planted with *A. mangium* (Hashim *et al.,* 2015). The plantation in Sarawak is established mainly in the central lowland region, generally comprising elevated wave-cut platforms developed from sedimentary rocks. The central region of the state area is dominated by the Red-Yellow Podzolic soils and is usually low in water-holding capacity with poor fertility, which limits the ability of the tree to grow efficiently (Lee *et al.,* 2015). The soil status in the central region dictates the type of vegetation to be planted, leading to only certain tree species with high tolerance being chosen for the forest plantation.

Forest plantation activities are challenging as the designated areas are in the post-deforested and degraded areas, where the soil and vegetation had been severely disturbed. Deforested and degraded lands have soil health issues as they are eroded and infertile (Sanchez *et al.,* 2003). Disturbed natural forests cause soil erosion, which leads to losses in nutrients, resulting in low nutrient stock om the soil (Cavalier *et al.,* 1999; Ishizuka *et al.,* 2000; Arifin *et al.,* 2008). Forest plantation sites are prepared using heavy mechanical machines during the establishment phase. This practice is commonly used to clear the plantation sites, followed by the stacking and burning of forest residuals. This leads to soil disturbance within the area, resulting in soil degradation and infertility (Cavelier *et al.,* 1999).

The capability of the soil to store nutrients is vital for the survival of trees (Weil & Brady, 2017). The physicochemical properties of the soil indicate whether it can support the efficient and effective growth of trees in every condition. The physicochemical properties of the soil affect the growth and wood quality of trees (Rigatto *et al.,* 2004). Macronutrients nitrogen (N), phosphorus (P) and potassium (K) are critical nutrients in many environments and are taken up in large quantities for biomass production in plants (Sankaran *et al.,* 2005). The vital nutrient for *A. mangium* in Malaysia is P (Srivastava, 1993). Fertiliser application can replenish the nutrient supply to maintain or even increase the productivity of *A. mangium*. A significant response in growth of 30-month-old *A. mangium* with the application of 26 – 27 P kg/ha in South Kalimantan was reported by Turvey (1996). However, in South Sumatra, the response to P fertiliser in 4-year-old trees was non-significant (Hardiyanto & Wicaksono, 2008). Balanced NPK fertilisers with good harvest-residue management resulted in a significant increase in height and diameter at breast height of 3-year-old *A. mangium* in the second rotation (Siregar *et al.,* 2006).

This study examines the physicochemical properties of soil of different stand ages and soil depths of an *A. mangium* plantation. Over time, the accumulation and decomposition of litterfall and debris occur in the plantation, which will change the soil's physicochemical properties, and more nutrients enter the soil. The high organic matter content in soil consequently will decrease the bulk density. A recent study in a Chinese pine plantation showed that available phosphorus and soil bulk density decreased with plantation age (Dang *et al*., 2017). This means that older plantation soil is loose, well aggregated, have high porosity and organic matter. Soil that has relatively high bulk density is soil that is rich in sand since the total pore space of sand is the lowest compared with silts or clay soils. Soil bulk density exceeding 1.80 g/cm^3 is considered root limiting (USDA, 2001). Soil bulk density increases with soil depth as the organic matter, aggregation, and root penetration become lesser through the subsurface and increasingly compacted (Blake & Hartge, 1986).

Soil organic matter is a crucial indicator for the fertility status of the soil. Soils in planted forests usually have low organic matter content, as well as low clay and nutrient contents. Increasing organic matter improves the nutrient status of the soil and is also assumed to improve biological activity and soil structure (Blake & Hartge, 1986; USDA, 2001). *Rhizobiales***,** in the order Alphaproteobacteria, are found in many root nodules of legumes, such as *A. mangium*, which fixes nitrogen from the atmosphere that increases with forest age (Cavelier *et al.,* 1999). It has been shown that organic matter content in the topsoil of the reclaimed soil increases with reclamation age (Li *et al.,* 2018). Organic matter in the soil is key in assessing soil quality in tropical regions (Paniagua *et al.,* 1999). In Malaysia, the soil organic matter and nitrogen content are the two most crucial soil constituents that correlate with most of the physicochemical and biological properties of the soil (Yaacob *et al.,* 1979).

Old forest stands are expected to have higher carbon and lower nutrients contents, bulk density and pH compared with young forest stands (Turvey, 1996). The increased soil organic matter in older plantations is due to higher litter accumulation compared with younger stands. The low availability of nutrients in the older stand is due to weathering and greater absorption by roots under the high availability of water. The age of individual trees and the successional stage of the ecosystem influence plant-soil interactions (Kardol *et al.,* 2006; Gough *et al.,* 2008). The longer the interaction, the more changes occur in the rhizosphere (De Deyn *et al.,* 2008). Vegetation strongly affects soil volume, chemistry, and texture, which in turns affect various vegetation characteristics, including productivity, structure and floristic composition (Brant *et al*., 2006).

Several studies on soil physicochemical properties in natural and planted forest areas were conducted in Sarawak (Hardiyanto & Wicaksono, 2008; Perumal *et al.,* 2015; Tanaka *et al*., 2015). However, the effect of stand age on soil physicochemical properties within the large scale of commercially planted forest stand ages, particularly on *A. mangium* is limited. Afforestation changes the microclimate and land-use pattern in an area. *Acacia mangium* plantation affects soil fertility. Changes in soils associated with the planting of this species are physical and chemical changes and the composition of nutrients concerning soil depth. There have been no systematic studies on the effect of *Acacia mangium* plantation stand ages on soil physicochemical properties. The main objective of this study is to examine the major soil physical and chemical properties in various *A. mangium* stand ages and soil depths.

Materials and Methods

Study Site

This study was conducted at a forest plantation owned by Daiken Sarawak Sdn Bhd, a Malaysian-Japanese joint-venture company incorporated on February 15, 1994. The plantation is located approximately 60 km from Bintulu in Sarawak, Malaysia, at 03˚21.347' N and 113°27.129' E and is within 30 m to 160 m above sea level. The site receives a total annual rainfall of 3,755 mm, and the average temperature ranges from 23°C to 32°C (Sa'adi *et al.,* 1996). The plantation was originally a secondary forest and later planted with *A. mangium*. The vegetation was mechanically cleared during site preparation and establishment, and the company observed zero burnings. Six months after planting, the seedlings were supplied with 40 g of slow-release fertiliser (SK 10-26-10+3MgO). The planting distance was set at 3 m × 3 m, making the number of seedlings planted in one hectare 1111. Hence, fertiliser use is about 44.44 kg ha^{-1}, which is considered low.

Field samplings were conducted at five stand ages, which were 3.7, 5.8, 8.5, 10.8 and 12.7 years old, respectively. These stands were selected to represent the growth performance spaced about two years apart. One secondary forest area within the plantation was also sampled, which represent the reference site. The type of soil in the Daiken Sarawak Sdn Bhd plantation is a well-drained Bekenu series characterised by fine, loamy, siliceous, isohyperthermic and red-yellow to yellow. The main factor restricting the use of this soil is its low fertility status (Paramananthan, 2006). The initial soil conditions were considered to be similar for all stands. The terrain was undulating with a slope of less than 6˚ and covered by the same vegetation type.

Sample Collection

Five 30 m × 30 m (4,500 m^2) sample plots were established randomly within five different stand ages. For soil characteristic determination, only one plot from each stand age was chosen. Three random points were selected at every corner within each study plot and identified for soil sampling. A total of 12 points are assigned in each plot of each stand age. Soil samples were collected at a depth of 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm using a hand auger. Soil samples from the selected secondary forest area (for reference) were also collected similarly. The field-sampling method for soil sampling in all study plots was adapted from Wasli *et al.* (2009). The soil samples from each point were mixed to get a composite sample for each soil layer. The soil samples were air-dried before being sieved through a 2 mm mesh for physicochemical analysis.

Determination of Soil Physical Properties

Particle size distribution was determined using the pipette method (Gee & Bauder, 1986). This was done to separate the inorganic soil particle into sand, silt and clay fractions (Soil Survey Report, 1996). Soil bulk density was determined and collected in the plantation area at a depth of 0-20 cm using a 100 cc core sampler with the ratio of the dry mass of soil to the bulk volume of the soil core. This experiment was performed by oven-drying the soil samples at 105°C for 24 hours. The bulk density value was used for further soil physical analysis, such as in the determination of porosity, water content and moisture content of the soil.

Determination of Chemical Properties

The soil pH was measured in distilled water, H_2O, with a soil-to-solution ratio of 1:5 using the glass electrode method. Using a Carlo Erba elemental analyser, the total carbon (T-C) content was determined on a > 100 mesh using flash fry combustion. The total nitrogen (T-N) content was determined with Kjeldahl acid digestion using Digesdahl and tested with Hach DR/890 Portable Colorimeter. The contents of exchangeable bases, Ca, Mg, K and Na were measured after successive extraction (three times) using 1 M ammonium acetate, NH4-OAc adjusted to pH 7.0 and 10% NaCl, respectively. The concentrations of Ca, Mg, K and Na were determined using the atomic absorption spectrophotometer (AAS) (Thermo Scientific, Ice Series 3500). Available phosphorus (Avail. P) content was measured using the Bray II method (Bray & Kurtz, 1945) with ultraviolet-visible (UV) spectrophotometer at a wavelength of 710 nm (Jasco V-630).

Data Analysis

The data of soil physicochemical properties were statistically analysed using a one-way ANOVA to determine any significant differences between stand ages and between soil depth. All the statistical tests were performed using SPSS version 24.0 for Windows (IBM Corp, 2016).

Results and Discussion

Soil Physicochemical Properties of Various Acacia mangium Stand Ages

For soil comparison of physical and chemical properties among stand ages, only the layer of 0-20 cm soil depth was considered. This is because the topsoil layer is the most important layer for plant growth. It consists of O and A horizons containing humus or accumulated organic matter and is available for plant nutrition. Soil physical properties within various stand ages of the *A. mangium* plantation area and the reference soil are shown in Table 1.

Soil textural characteristics values of all stand ages areas, including reference soil, were similar. The clay content was within the range of 24.7% to 28.5%, silt content 13.5% to 19.4% and sand content 58.6% to 61.9%. The soil texture is sandy clay loam. The clay content recorded in this study is higher than those reported for *A. mangium* plantations in other studies. The clay content of the *A. mangium* plantation studied by Lee *et al.* (2015) was 19.2% to 23.7% and Tanaka *et al.* (2015) found that the average clay content was 20%. A huge variation of clay content in *A. mangium* plantation in Andalau, Brunei, was found, which ranges from 1% to 30% (Matali & Matali, 2015).

The soil chemical properties within 20 cm soil depth in various stand ages of the *A. mangium* plantation and the reference soil are

Table 1: Soil physical properties within the various stand ages of the *Acacia mangium* plantation and reference soil in Bintulu, Sarawak, Malaysia

Soil Depth (cm)	Stand Age (years)	Soil Texture	Clay (%)	Silt (%)	Sand (%)	Bulk Density (g/mL)
0 – 20	3.7	Sandy clay loam	28.9±0.9^{a*}	15.9±0.5^{a}	58.6±2.6^{a}	1.6±0.3^{b}
	5.8	Sandy clay loam	25.4±2.0^{a}	14.3±1.7^{a}	60.3±3.7^{a}	1.5±0.2^{b}
	8.5	Sandy clay loam	24.9±2.2^{a}	13.5±6.3^{a}	61.5±6.4^{a}	0.3±0.1^{a}
	10.8	Sandy clay loam	24.7±2.3^{a}	15.7±2.7^{a}	59.7±0.5^{a}	0.7±0.8^{b}
	12.7	Sandy clay loam	25.6±4.2^{a}	17.5±0.1^{a}	61.9±5.1^{a}	0.7±0.3^{b}
	Reference	Sandy clay loam	25.5±0.2^{a}	15.4±1.1^{a}	58.1±1.9^{a}	0.8±0.0^{b}

*Mean ± standard deviation: Values in the same column followed by different letters indicate significant differences among stand ages at $P < 0.05$ using Tukey's HSD test shown in Table 2. Soil organic matter (SOM) in all stands ages ranged from 2.4% to 5.1%. The SOM in the reference soil was significantly higher than the planted areas. Although not significantly different, there was an increasing trend of SOM (%) with stand age in the *A. mangium* plantation. The results indicated that the organic content in the soil is approaching the recovery pool of soil carbon at the age of 12.7 years old. The soil pH ranged from 3.2 to 4.7 and can be classified as extremely acidic (Sparks, 2017). The pH values decreased as the stand age increased. The CEC values in all study areas were low, in the range of 6.8 to 10.7 cmolc/kg, whereas the CEC value in the reference soil was significantly higher than the other *A. mangium* planted area. The lowest CEC values recorded were in 3.7- and 5.8-year-old *A. mangium* stand. The CEC values of all stand ages were within 6.84 to 8.53 cmolc/kg.

The value of the T-C content in the planted area soil profiles appeared to be similar for all stand ages. The T-C value in the reference soil was significantly higher than the *A. mangium* planted area, except for the 12.7-year-old stand. The T-N contents in all stand ages ranged from 0.4 g/kg to 1.0 g/kg. Generally, the T-N values decrease with an increase of stand ages. The highest T-N value among all *A. mangium* planted areas was in the 12.7-year-old stand at 0.80 g/kg, while the reference soil recorded a value of 1.0 g/kg. The carbon over nitrogen (C/N) ratio was within the range of 28.8 to 75.3, where the values did not differ between stand ages.

The exchangeable Ca and Na mean values among all stand ages and reference soil were similar. Exchangeable Mg in the reference soil was found to be significantly higher than in the planted areas. The *Acacia mangium* planted areas were observed to have similar exchangeable Mg mean values in all stand ages.

Table 2: Soil chemical properties within the various stand ages of the A. *mangium* plantation and reference soil in Bintulu, Sarawak, Malaysia

Soil Depth (cm)	Stand Age (years)	SOM (%)	pH (H_2O)	CEC (cmolc/kg)	T-C (g/kg)	T-N (g/kg)	C/N Ratio
0 – 20	3.7	3.9±0.6[a]*	4.7±0.2[b]	7.1±0.8[ab]	22.4±3.5[a]	0.7±0.3[a]	37.4±16.0[a]
	5.8	2.9±0.4[a]	3.7±0.0[a]	8.5±0.7[b]	18.2±2.6[a]	0.6±0.2[a]	30.6±16.1[a]
	8.5	2.9±0.3[a]	3.5±0.3[a]	8.5±0.5[b]	17.3±1.9[a]	0.4±0.3[a]	31.5±9.5[a]
	10.8	2.4±0.3[a]	3.3±0.1[a]	7.9±0.8[b]	13.7±1.9[a]	0.5±0.5[a]	28.9±4.8[a]
	12.7	4.2±1.1[a]	3.2±0.3[a]	6.8±0.7[a]	19.2±1.0[a]	0.8±0.1[a]	31.4±16.6[a]
	Reference	5.1±0.7[b]	4.1±0.7[b]	10.7±0.9[c]	29.6±0.4[b]	1.0±0.3[b]	30.1±8.2[a]

Soil Depth (cm)	Stand age (years)	Exch. Ca (cmolc/kg)	Exch. Mg (cmolc/kg)	Exch. K (cmolc/kg)	Exch. Na (cmolc/kg)	Avail. P (mg/kg)
0 – 20	3.7	1.0±0.[a*]	0.2±0.9[b]	0.10±0.4[a]	0.06±0.0[a]	12.8±1.9[b]
	5.8	0.3±0.0[a]	0.2±0.4[a]	0.10±0.2[a]	0.06±0.0[a]	9.0±0.9[b]
	8.5	0.7±0.2[a]	0.5±0.2[b]	0.18±0.2[b]	0.06±0.0[a]	6.1±0.9[a]
	10.8	0.5±0.4[a]	0.3±0.6[b]	0.11±0.2[a]	0.07±0.0[a]	8.4±1.1[b]
	12.7	0.4±3.4[a]	0.2±0.2[b]	0.11±0.2[a]	0.05±0.0[a]	10.2±4.7[b]
	Reference	1.7±1.4[a]	0.7±0.2[c]	0.12±0.3[a]	0.07±0.0[a]	13.9±1.6[b]

*Mean ± standard deviation: Values in the same column followed by different letters indicate significant differences among stand ages at $P < 0.05$ using Tukey's HSD test

The reference site soil profile recorded higher values for exchangeable K than the other stand ages and reference soil. The available P mean values in the 12.7-year-old stand and reference area were significantly higher than the other stand ages. The available P increased with stand age due to the accumulation of P when the *A. mangium* stands get older.

The soil physical properties are vital for air and water movement in the soils, which then influences the soil's ability to provide essential moisture, air, and nutrients for trees to grow. The reference plot recorded the highest SOM and lowest bulk density. Increased SOM with plantation age also saw a decrease in soil bulk density. Higher organic matter consequently reduced the bulk density (Dang *et al.,* 2017). Pores in soil developed due to roots growth, worms and other microbial structures (Dang *et al.,* 2017; Ali *et al.,* 2019). *Acacia mangium* with a high growth rate led to a high proportion of carbon content being retained to the stand biomass and not returned to the soil (Yamashita *et al.,* 2008). The increase of SOM and T-C with stand age can be attributed to the fact that older stand accumulated decomposed litterfall, providing carbon constituents to the soil (Perumal *et al.,* 2015). The high density of shrubs and the understorey layer gives higher shading to the older stand areas, leading to them having favourable moisture that increases the decomposition rate (Bot & Benites, 2005).

Soil texture determines the rate of water movement through the saturated soil and is responsible for the water capacity in the soil to be absorbed by the plant conditions (Berry *et al.,* 2007). The high accumulation of clay percentage increases the moisture content in most of the study area as the ability of the soil to hold the water increases (Lu *et al.,* 2002). High clay content and organic matter in the soil will also increase the CEC and the pH buffering capacity in the soil (Berry *et al.,* 2007). Soil T-N in the oldest stand age area (12.7 years old) was higher than the others due to the higher density of dead leaves within the soil surface of the site. *Acacia* leaves have a high rate of decomposition; thus, the high density of *Acacia* N-enriched leaves will increase the high concentration of T-N in the soil (Reversat, 2001; El Tahir *et al.,* 2009; Morris *et al.,* 2011). Besides, the denser root formation in older stand ages also boosted the N-fixing microbial activity decomposition (Matali & Matali, 2015). The reduction trends of soil T-N in 3.7- to 8.5-year-old stands are due to the increases of T-N uptake by the fast-growing *A. mangium* trees with a lower rate of organic decomposition.

The soil pH level in the 3.7-year-old *A. mangium* area was the highest (less acidic) than the other study area (excluding the reference soil) due to the site preparation activities before the establishment of *A. mangium* as the whole area was primarily cleared-felled from the previous vegetation, which was a secondary forest. Hence, the biomass residuals in soil caused the soil acidification process to be minimised as soil nutrient uptake was relatively low and the soil input from the litterfall and other biomass residuals was high (Jobbágy & Jackson, 2001). This observation is contrary to (Rhoades & Binkley, 1996), as they stated that the pH value often decreased due to plantation establishment. The decline of pH value in the older stand areas in this study was due to litterfall and is related to the organic acid association, which led to an acceleration of organic matter decomposition. This is attributed to the SOM increasing with stand age (Table 1), leading to the formation of soil humic acid (Bot & Benites, 2005). Humic acids are a significant component of humic substances, the major organic constituents of soil humus produced by the biodegradation of dead organic matter.

The higher density of N-enriched litterfalls in older stand ages also leads to a higher nitrification rate, releasing the protons and soil acidification (Li *et al.,* 2018). This study agrees with Yamashita *et al.* (2008), as the exchangeable bases positively influence the soil pH (Table 2). The translocation of bases cations from soil to the standing biomass will increase the soil acidification and decrease of concentration of exchangeable bases in soil

(Yamashita *et al.,* 2008). A similar trend was reported by Lee *et al.* (2015) but was in contrast to Sanchez *et al*. (2003), who stated that the soil pH of *A. mangium* plantation increased five years after planting. In contrast, Hardiyanto and Wicaksono (2008) reported no change of pH value in the soil in that same period.

The CEC value was higher in 5.8- and 8.5-year-old *A. mangium* stand age areas due to the negative charges from the clay minerals (Berry *et al.,* 2007). The higher concentration of exchangeable bases within the younger stand ages was due to the lower rate of bases turnover to the plant from the soil. The high organic matter will increase the soil fauna to the soil (Bot & Benites, 2005). The CEC values are affected by the significant reduction of organic matter in the soil (Berry *et al.,* 2007). The high concentration of SOM contained higher biological accumulation that contributes to more Mg and Ca concentration in the soil (Soto & Diazfierroz, 1993). The increasing trend of base contents in 8.5-year-old plantation sites was due to the stands having achieved a steady state of cation gain and loss in due to basescycling by the trees. This study concurred with Ekukinam *et al.* (2014), who found that the exchangeable base values of a 7-year-old rubber tree area were relatively higher than the 16-year-old site.

The available P was higher in the 3.7-year-old area, probably because of the trees' low P consumption during the very early growing stage. Furthermore, *Acacia* litterfalls and weathering of nutrients mineralisation from parent rock materials contribute to the high availability of P formation (El Tahir *et al.,* 2009). However, as the stand gets older, there was a reduction in available P, which agrees with the observation made by Lee *et al.* (2015). The low concentration of soil-available P-value in the 8.5-year-old stand area may be due to the active P uptake during the rapid growth period. This observation suggests a high P consumption in the trees during the early growth period until they reach 8.5 years old. Besides, the high rate of annual rainfall occurring in the tropical climate is one of the factors that could reduce P concentration due to soil runoff and erosion (Bargali *et al.,* 1993). Overall, the soil physicochemical properties obtained from the current study in the *A. mangium* plantation depicted that the soil physical quality and nutrient contents were decreasing with stand age. Soil properties in 10.8- and 12.7-year-old areas are beginning to acquire the same properties as in the reference area.

Soil Physicochemical Properties with Soil Depth in Different Stand Ages and Reference Soil

The soil textural characteristic values in the study area showed that the sand content decreased while clay and silt contents increased with soil depth. The sand content in the top horizon of 12.7-year-old stand and the reference area was significantly higher than the lower zones. The clay and silt contents in 60 cm and above soil depths were significantly high in the 12.7-year-old stand and the reference area. Generally, the soil texture for all horizons is sandy clay loam, which is loam soil with a higher proportion of clay. The coarse sandy soil will create good aeration for root growth, but the water movement would be quickly drained away (White, 1997). Sandy soils have low erodibility because of their high permeability and low water runoff; hence erosion is often low (Yang *et al.,* 2018). On the other hand, the high clay level has a more excellent water holding capacity, which can hold water for a long time due to its small particle that fit closely together (Lu *et al*., 2002). Erodibility is also low for clay-rich soils because clay particles stick together into larger aggregates that resist detachment (Yang *et al.,* 2018).

Bulk density increased with depth in all stand ages and reference areas, except for the 5.8- and 8.5-year-old stands (Table 3). The upper horizons of all samples recorded lower bulk density than the lower horizons, except for the 3.7-year-old stand. *In-situ* observation showed that the organic matter, aggregation, and root penetration became lesser with soil depth, making it more compacted and less porous. High bulk density is considered with the sandy soil since its total pore space in sands is the lowest compared to silt or clay.

The chemical properties of the soil under various age stands and reference sites are shown in Table 4. The SOM in all areas of soil profiles decreased with the soil depth (Table 3). This result agrees with Lee *et al.* (2015) and Perumal *et al.* (2015). After a depth of 60 cm, significant low SOM values were recorded at the 8.5-, 10.8- and 12.7-year-old stand age soil horizons and the reference site. Generally, the pH values increased with depth, especially in the 5.8-, 10.8- and 12.7-year-old stands. The pH values in all soil depths were below 4.0 for all stand ages, except for the 3.7-year-ild site. The pH values of different soil depths in the

Table 3: Soil physical properties in different stand ages and soil depths of the *A. mangium* plantation and the reference site in Bintulu, Sarawak, Malaysia

Age (years)	Soil Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk Density (g/mL)
3.7	0-20	28.5±0.9[a*]	15.9±0.5[a]	58.6±2.6[a]	1.6±0.3[a]
	20-40	27.9±0.3[a]	15.8±0.1[a]	56.2±2.6[a]	1.7±0.5[a]
	40-60	28.8±0.5[a]	16.4±1.1[a]	55.1±0.6[a]	1.7±0.7[a]
	60-80	29.2±0.5[ab]	16.4±0.0[a]	54.4±2.1[a]	1.9±0.1[a]
	80-100	30.8±0.1[b]	16.0±0.3[b]	53.1±1.7[a]	1.9±0.2[a]
5.8	0-20	25.4±2.0[a]	14.3±1.7[a]	60.3±3.6[b]	1.5±0.7[a]
	20-40	27.4±7.3[a]	14.8±8.2[a]	57.8±18.2[a]	1.5±0.7[a]
	40-60	29.1±8.1[a]	15.2±2.6[a]	55.8±14.5[a]	1.8±0.1[ab]
	60-80	31.7±11.3[a]	14.3±7.4[a]	54.0±15.0[a]	1.9±0.3[b]
	80-100	32.6±4.1[a]	16.3±0.5[b]	51.1±11.2[a]	1.9±0.1[b]
8.5	0-20	24.9±12.2[a]	13.5±6.3[a]	61.5±6.4[b]	0.3±0.1[a]
	20-40	24.8±11.1[a]	14.2±1.3[a]	60.9±22.7[b]	1.3±1.0[b]
	40-60	24.9±12.2[a]	13.6±5.6[a]	61.5±16.4[b]	1.4±0.1[b]
	60-80	26.2±11.5[b]	15.1±2.5[a]	57.9±22.4[b]	2.1±0.1[b]
	80-100	28.8±14.5[c]	26.2±7.5[b]	45.0±17.6[a]	2.1±0.1[b]
10.8	0-20	24.7±2.3[ab]	15.6±2.7[a]	59.6±0.5[b]	0.7±0.8[a]
	20-40	25.0±0.5[a]	9.9±2.2[a]	58.5±14.9[b]	1.1±0.9[ab]
	40-60	24.9±2.3[ab]	14.7±0.7[a]	57.5±12.3[a]	1.3±1.1[ab]
	60-80	25.3±4.6[ab]	15.6±2.7[a]	56.0±3.3[a]	1.3±1.2[ab]
	80-100	25.5±1.8[b]	18.5±10.3[b]	56.0±4.2[b]	1.8±0.1[b]
12.7	0-20	25.6±4.6[a]	15.4±0.0[a]	61.9±5.1[c]	0.7±0.3[a]
	20-40	26.9±0.0[a]	16.8±0.7[a]	56.3±8.1[bc]	1.2±0.9[a]
	40-60	26.9±0.0[b]	17.1±1.0[a]	55.9±1.2[ab]	1.4±0.3[a]
	60-80	27.6±4.2[c]	19.2±0.3[b]	53.1±0.8[a]	1.8±0.2[a]
	80-100	27.4±1.0[c]	20.8±1.9[b]	51.7±1.6[a]	1.8±0.8[b]
Reference	0-20	25.5±0.2[a]	16.4±0.1[a]	58.1±1.9[c]	0.1±0.1[a]
	20-40	26.3±0.6[a]	17.5±0.3[a]	56.2±0.7[c]	0.9±0.0[a]
	40-60	26.9±0.4[a]	18.7±0.4[ab]	54.4±2.7[b]	1.9±0.0[ab]
	60-80	27.4±0.2[a]	19.6±0.1[b]	52.9±0.7[b]	1.9±0.3[b]
	80-100	29.7±0.2[b]	19.7±0.3[b]	50.6±0.7[a]	1.9±0.1[b]

*Mean ± standard deviation: Values in the same column followed by different letters indicate significant difference at $P < 0.05$ using Tukey's HSD test

3.7-year-old stand and the reference site were higher in the range of 4.46 to 4.67 and 4.11 to 4.23, respectively. pH values lower than 6 will affect the Ca contents in the soil, leading to a failure in plant uptake (Larcher, 2003). However, *A. mangium* is adapted to acidic soils and even grows in soils with pH that is less than 4.0 (Franco & de Faria, 1997; Midgley & Turnbull, 2003). The effective CEC in all stands was found to be similar in all soil horizons, except for the 10.8-year-old stand age (Table 4). The CEC of the subsoil of the 10.8-year-old stand was significantly higher than the top horizon (0-20 cm soil depth). The total carbon of

Table 4: Soil chemical properties in different stand ages and soil depths of the *A. mangium* plantation area and the reference soil in Bintulu, Sarawak, Malaysia

Age (years)	Soil Depth (cm)	SOM (%)	pH (H_2O)	CEC (cmolc/kg)	T-C (g/kg)	T-N (g/kg)	C/N Ratio
3.7	0-20	2.4±0.3a*	4.7±0.2^{a}	7.1±0.8^{a}	22.4±3.5^{a}	0.7±0.3^{a}	37.4±16.0^{a}
	20-40	1.9±0.4a	4.5±0.2^{a}	6.5±1.3^{a}	19.5±3.3^{a}	0.6±0.0^{a}	35.6±43.9^{a}
	40-60	1.9±0.7a	4.6±0.4^{a}	6.3±0.6^{a}	14.8±0.4^{a}	0.4±0.1^{a}	44.4±17.3^{b}
	60-80	1.3±0.4a	4.5±0.1^{a}	7.2±1.1^{a}	15.0±4.3^{a}	0.4±0.2^{a}	41.8±18.4^{ab}
	80-100	1.5±0.7a	4.5±0.1^{a}	5.9±0.6^{a}	15.3±1.5^{a}	0.3±0.1^{a}	63.3±23.7^{c}
5.8	0-20	2.8±0.4^{a}	3.7±0.0^{a}	8.5±0.7^{a}	18.4±2.1^{c}	0.6±0.2^{a}	30.6±49.1^{a}
	20-40	2.8±0.5^{a}	3.7±0.2^{ab}	8.4±0.7^{a}	17.2±2.6^{bc}	0.5±0.2^{a}	42.1±032.4^{a}
	40-60	2.4±0.2^{a}	3.8±0.2^{ab}	6.9±0.4^{a}	13.8±1.3^{ab}	0.2±0.1^{a}	51.1±70.8^{a}
	60-80	2.3±0.2^{a}	3.9±0.1^{ab}	7.1±1.8^{a}	13.2±91.2^{a}	0.1±0.8^{a}	60.7±49.2^{b}
	80-100	2.4±0.4^{a}	3.4±0.1^{b}	7.3±1.2^{a}	12.9±1.1^{a}	0.2±0.8^{a}	69.6±40.1^{b}
8.5	0-20	2.9±0.3^{b}	3.5±0.3^{a}	8.5±0.5^{a}	17.3±1.9^{b}	0.4±0.3^{a}	31.5±9.6^{a}
	20-40	2.6±0.5^{b}	3.7±0.3^{a}	7.9±0.9^{a}	14.8±2.9^{ab}	0.3±0.1^{a}	63.5±43.1^{b}
	40-60	2.2±0.3^{ab}	3.8±0.2^{a}	7.5±0.4^{a}	12.8±1.5^{ab}	0.3±0.1^{a}	54.3±10.5^{a}
	60-80	2.0±0.2^{a}	3.8±0.0^{a}	8.1±2.3^{a}	8.2±1.0^{a}	0.4±0.1^{a}	66.3±37.0^{b}
	80-100	1.4±0.2^{a}	3.8±0.1^{a}	8.6±1.8^{a}	11.8±1.3a	0.2±0.1^{a}	55.5±17.3^{a}
10.8	0-20	3.9±0.6^{b}	3.3±0.1^{a}	7.92±0.8^{b}	13.7±1.9a	0.5±0.5^{a}	28.9±4.8^{a}
	20-40	3.4±0.1^{ab}	3.5±0.3^{ab}	6.65±1.1^{a}	10.7±2.0^{a}	0.3±0.2^{a}	51.3±42.6^{a}
	40-60	2.6±0.1^{ab}	3.6±0.1^{bc}	5.73±0.9^{a}	11.5±3.9^{a}	0.4±0.2^{a}	33.5±18.2^{a}
	60-80	2.6±0.7^{a}	3.7±0.1^{bc}	5.63±0.0^{a}	7.3±2.6^{a}	0.2±0.1^{a}	53.5±37.6^{a}
	80-100	2.6±0.3^{a}	3.8±0.0^{b}	5.12±0.5^{a}	8.5±4.1^{a}	0.2±0.1^{a}	45.5±12.2^{a}
12.7	0-20	4.2±1.1^{b}	3.2±0.3^{a}	6.8±0.7^{a}	19.2±1.0^{a}	0.8±0.6^{a}	31.4±16.6^{a}
	20-40	3.0±0.6^{a}	3.7±0.1^{ab}	6.1±0.6^{a}	17.6±3.2^{a}	0.5±0.1^{a}	43.2±8.5^{a}
	40-60	2.6±0.2^{a}	3.8±0.1^{a}	6.2±0.4^{a}	15.2±0.9^{a}	0.3±0.2^{a}	47.9±23.1^{a}
	60-80	3.4±0.2^{a}	3.9±0.1^{a}	5.52±0.7^{a}	19.8±1.3^{a}	0.5±0.3^{a}	29.3±10.3^{a}
	80-100	2.2±1.1^{a}	4.0±0.0^{c}	5.14±0.5^{a}	12.8±2.2^{a}	0.8±0.1^{a}	23.4±10.4^{a}
Reference	0-20	5.1±0.7^{c}	4.1±0.7^{a}	10.7±0.9^{a}	29.6±0.4^{a}	1.0±0.3^{b}	30.1±8.2^{a}
	20-40	3.6±0.5^{ab}	4.2±0.4^{a}	9.2±0.9^{a}	20.9±8.9^{a}	0.6±0.1^{a}	55.4±16.8^{a}
	40-60	3.0±0.5^{a}	4.2±0.3^{a}	8.1±2.4^{a}	17.6±12.8^{a}	0.4±0.1^{a}	42.1±4.3^{a}
	60-80	2.1±0.6^{a}	4.1±.2^{a}	8.6±0.7^{a}	16.3±3.3^{a}	0.7±0.3^{a}	30.2±20.1^{a}
	80-100	2.9±0.5^{a}	4.2±0.2^{a}	11.7±2.3^{a}	17.2±3.2^{a}	0.4±0.2^{a}	44.7±24.0^{a}

Age (years)	Soil Depth (cm)	Exch. Ca (cmolc/kg)	Exch. Mg (cmolc/kg)	Exch K (cmolc/kg)	Exch. Na (cmolc/kg)	Available P (mg/kg)
3.7	0-20	1.0±0.7[a*]	0.3±0.9[a]	0.1±0.1[a]	0.1±0.0[a]	12.8±1.9[c]
	20-40	1.2±0.7[a]	0.3±0.3[a]	0.1±0.1[a]	0.1±0.0[a]	6.6±1.4[b]
	40-60	0.6±0.3[a]	0.1±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	4.6±1.3[ab]
	60-80	0.8±0.6[a]	0.2±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	3.7±0.4[ab]
	80-100	0.5±0.3[a]	0.1±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	2.9±0.8[a]
5.8	0-20	0.3±0.2[b]	0.2±0.2[a]	0.1±0.1[a]	0.1±0.0[a]	9.0±1.7[d]
	20-40	0.2±0.4[ab]	0.2±0.1[a]	0.1±0.1[a]	0.1±0.0[a]	6.0±0.8[c]
	40-60	0.2±0.2[ab]	0.1±0.9[a]	0.1±0.0[a]	0.1±0.0[a]	2.6±1.1[b]
	60-80	0.2±0.9[a]	0.1±0.1[a]	0.1±0.2[a]	0.1±0.0[a]	1.2±0.6[a]
	80-100	0.2±0.2[a]	0.1±0.1[a]	0.1±0.2[a]	0.0±0.0[a]	0.5±0.4[a]
8.5	0-20	0.7±0.2[b]	0.5±0.2[a]	0.2±0.0[a]	0.2±0.2[b]	6.1±0.4[c]
	20-40	0.3±0.0[a]	0.3±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	5.1±0.7[bc]
	40-60	0.3±0.1[a]	0.2±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	3.6±1.5[b]
	60-80	0.3±0.1[a]	0.3±0.2[a]	0.1±0.0[a]	0.1±0.1[a]	1.4±0.9[ab]
	80-100	0.3±0.1[a]	0.3±0.3[a]	0.1±0.0[a]	0.1±0.0[a]	0.4±0.4[a]
10.8	0-20	0.5±0.4[a]	0.3±0.1[b]	0.1±0.0[a]	0.1±0.0[a]	8.4±1.1[c]
	20-40	0.2±0.1[a]	0.2±0.1[ab]	0.1±0.0[a]	0.1±0.0[a]	6.4±1.2[bc]
	40-60	0.3±0.0[a]	0.1±0.1[b]	0.1±0.0[a]	0.1±0.0[a]	4.7±0.2[ab]
	60-80	0.3±0.0[a]	0.1±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	4.1±0.1[ab]
	80-100	0.3±0.1[a]	0.1±0.1[a]	0.1±0.1[a]	0.1±0.0[a]	2.8±1.0[a]
12.7	0-20	0.4±3.4[a]	0.2±0.1[b]	0.3±0.1[b]	0.1±0.0[a]	10.2±4.7[c]
	20-40	0.3±0.1[a]	0.1±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	6.4±1.2[b]
	40-60	0.2±0.0[a]	0.1±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	5.5±1.6[ab]
	60-80	0.3±0.0[a]	0.1±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	4.2±0.9[ab]
	80-100	2.3±0.1[a]	0.1±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	3.2±0.7[a]
Reference	0-20	1.8±1.4[a]	0.7±0.2[a]	0.1±0.0[a]	0.1±0.0[a]	13.8±1.6[c]
	20-40	0.7±0.4[a]	0.3±0.3[a]	0.1±0.0[a]	0.1±0.0[a]	8.9±1.5[b]
	40-60	0.1±0.6[a]	0.4±0.3[a]	0.1±0.0[a]	0.1±0.0[a]	6.9±0.3[ab]
	60-80	0.4±0.2[a]	0.2±0.2[a]	0.1±0.0[a]	0.1±0.0[a]	4.5±0.2[ab]
	80-100	0.3±0.1[a]	0.2±0.1[a]	0.1±0.0[a]	0.1±0.0[a]	3.2±1.1[a]

*Mean ± standard deviation: Values in the same row followed by different letters indicate significant differences among sites at $P < 0.05$ using Tukey's HSD test; a) pH (DIW); b) Cation Exchange Capacity; c) T-C: Total Carbon; d) T-N: Total Nitrogen; e) Carbon/Nitrogen ratio; f) Exchangeable Bases (Ca, Mg, K, and Na); and, g) Available phosphorus

the soil profile in the 5.8- and 8.5-years old stand ages was generally higher at the upper horizons than the subsurface soil horizons (Table 4). The clay content in each horizon group and the decomposition rate of soil organic matter plays a significant role in the decreasing trend of T-C content with soil depth (Ohta & Effendi, 1992). There was no variation of T-N values and C/N ratio within the soil depth in all stand ages and reference sites.

In general, the exchangeable bases for Calcium (Ca), Magnesium (Mg) and Potassium (K) in the soil profile of all study areas did not vary greatly (Table 4). Exchangeable Ca and Na values were significantly higher in the upper horizons for only the 8.5-year-old stand age. The exchangeable Mg, K values were similar in all soil depths, except the 12.7-year –old stand, where the values were significantly higher in the upper horizons. The available phosphorus values in the upper horizons in all stand ages, including the reference soil, were higher in the upper horizons (Table 4). Overall, it was observed that the soil chemical properties were significantly higher within the shallower soil depth. This observation showed that the soil chemical content diminished with soil depth.

Generally, the nutrient concentration observed in this present study decreased with soil depth. The primary source of organic matter to the soil is the vegetation, root mats development and litterfalls that accumulated more on the topsoil (Perumal *et al.,* 2015; Tanaka *et al.,* 2015). The topsoil has a high density of biological organisms, creating more pore spaces for organic decomposition and nutrient synthesis (Bot & Benites, 2005). The subsoil also contains some nutrients concentration as the storage that will pump up slowly to the topsoil (Ohta & Effendi, 1992). The tropical climate also influences the concentration of the nutrients within the subsoils. The heavy rainfall in the plantation area will lead to nutrient mobility in the soil, causing the nutrient particles to leach to the deeper soil layers (Tanaka *et al*., 2015; Matali & Matali, 2016).

The SOM and T-C decreased with soil depth due to decreasing vegetation and tree litters with depth. The primary sources of organic matter to the soil are litterfall, mainly found on the soil surface (Rahman *et al.,* 2012). Low bulk density is indicated by the loose, well aggregated, high porosity and those rich in organic matter in the soil (Blake & Hartge, 1986). The high T-N content within the topsoil is due to the ability of the *A. mangium* stand to undergo nitrogen-fixing by itself (Lee *et al*., 2015). The decreasing trend of T-N content with the soil depth was probably due to the nitrogenous compounds within the subsoils being more resistant to microbial attacks than in the topsoil (Ohta & Effendi, 1992).

Conclusion

Information on the soil physicochemical properties status in forest plantation areas of various stand ages is vital to understand and sustain the growth performance of the *A. mangium* plantation. Most physicochemical properties decrease with soil depth. The soil texture of all stand ages was sandy clay loam soil. For chemical properties, the soil T-N differs with the stand ages, and the 12.7-year-old stand recorded the highest value. Generally, soil pH decreased with stand age. Exchangeable bases varied, but the values were higher in the younger stand ages. The available P was higher in the 3.7-year-old stand, and it decreased with stand age. Overall, the soil pH is considered to be extremely acidic, and this study is strong evidence that *A. mangium* growth is not affected by low soil pH. The soil physicochemical properties in the 12.7-year-old stand were the closest to the soil properties of the reference site.

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